

# Solid Waste Management Requirements Definition for Advanced Life Support Missions - Results

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## ABSTRACT

Prior to determining what Solid Waste Management (SWM) technologies should be researched and developed by the Advanced Life Support (ALS) Project for future missions, there is a need to define SWM requirements. Because future waste streams will be highly mission-dependent, missions need to be defined prior to developing SWM requirements. The SWM Working Group has used the mission architecture outlined in the System Integration, Modeling and Analysis (SIMA) Element Reference Missions Document (RMD) as a starting point in the requirement development process. The missions examined include the International Space Station (ISS), a Mars Dual Lander mission, and a Mars Base. The SWM Element has also identified common SWM functionalities needed for future missions. These functionalities include: acceptance, transport, processing, storage, monitoring and control, and disposal. Requirements in each of these six areas are currently being developed for the selected missions. This paper reviews the results of this ongoing effort and identifies mission-dependent resource recovery requirements.

## INTRODUCTION

Future space missions will place humans in space for increasing periods of time and without the opportunity for resupply. The longest continuous period that any US crewmember has spent in space is 188 days (Mir 21 - Shannon Lucid). However, the presence of the ISS may allow for this duration to be surpassed. Mars missions have been evaluated up to 15 years in duration. These long missions will produce large quantities of solid waste.

Waste is already a problem for ISS, and will get worse as mission duration increases. A primary objective of the ALS Project is to provide technologies that reduce life cycle costs, improve operational performance, promote self-sufficiency, and minimize expenditure of resources for long-duration missions (ALS Project Plan, 2002). We need to develop improved technologies for all aspects of solid waste disposition. Unfortunately, we cannot fund all interesting avenues of technology development, and must select carefully which projects appear to be most promising.

Until recently, no systematic process for technology selection had been developed, documented, and officially implemented for the ALS Project. The SWM Element has begun the development of such a methodology for technology selection. This method is outlined briefly in this paper and is documented in detail in the ALS SWM R&TD Plan (Alazraki, 2001). This paper presents progress to date on a key element of that process: requirements development.

The top-level approach that the ALS SWM Element has taken to focus SWM R&TD is shown in **Figure 1**. Each block in **Figure 1** is provided with an identification number in the upper left-hand corner. Standard process diagram shapes are used to depict starting and ending points (ovals), inputs (parallelograms), processes (rectangles), and decisions (diamonds). To date, progress has been made on blocks 1 through 10 of the ALS SWM Technology Selection Process. The first step of requirements identification is specification of a reasonable range of possible future missions and their top-level life support system (LSS) architectures (blocks

2 through 5). The missions used by the SWM Element for this purpose are those, which are currently depicted

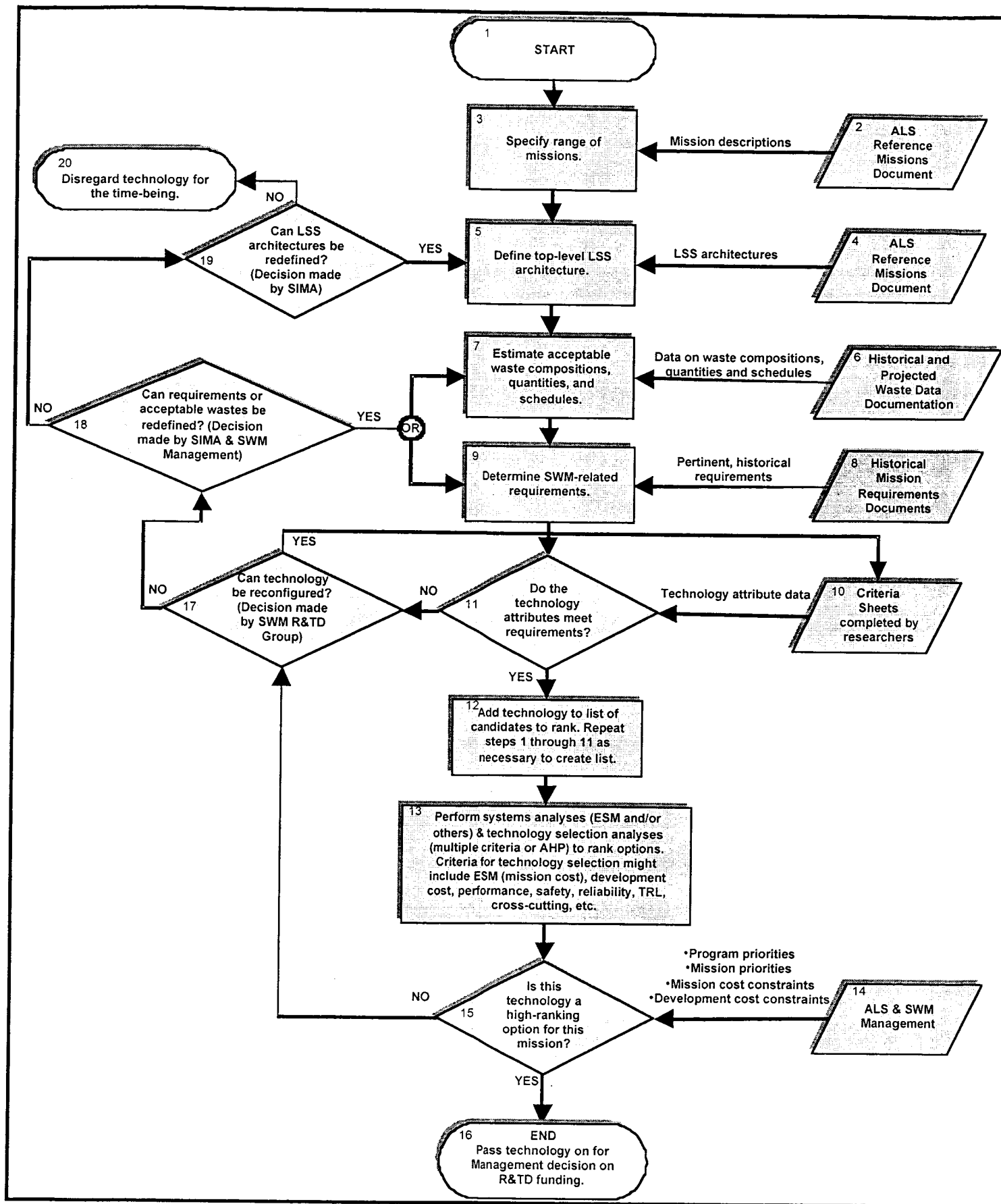


Figure 1. The ALS SWM Technology Selection Process

in the ALS Reference Missions Document (RMD) (Stafford et al, 2001). These reference missions are recognized as being a starting point only. Thus, evaluations might be considered that look at other configurations where there seems likely to be a benefit. The SWM requirements are not explicitly restricting waste management to these configurations alone. Requirements for SWM on future missions are being developed to state certain objectives, rather than to state *how* those objectives will be achieved.

Next, waste stream quantities, compositions and generation schedules are predicted (blocks 6 and 7). Solid waste production is highly mission-dependent. Initial estimates of the composition, quantity and generation schedule of solid wastes are needed in order to develop SWM requirements. After initial estimates are made, successive iteration can lead to refinement. Once missions, LSS architectures and expected waste streams have been defined, mission requirements may be developed (blocks 8 and 9). Information about current or potential SWM technologies must then be collected from SWM researchers and technology developers (block 10). Once requirements have been established and technology information has been collected, the needs (requirements) may be compared with the available technologies (block 11). This enables ALS management to make informed decisions about ALS SWM R&TD funding.

This paper is the third of a set of three papers that describe the reasoning and process of developing requirements for the missions of interest to the ALS SWM Element. The first paper in the series (Hogan et al, 2002) provides a general discussion of the critical obstacles and possibilities associated with solid waste management in long-duration human missions. The second paper in the series (Levri et al, 2002) addresses some of the difficulties in writing requirements for missions that are not completely defined.

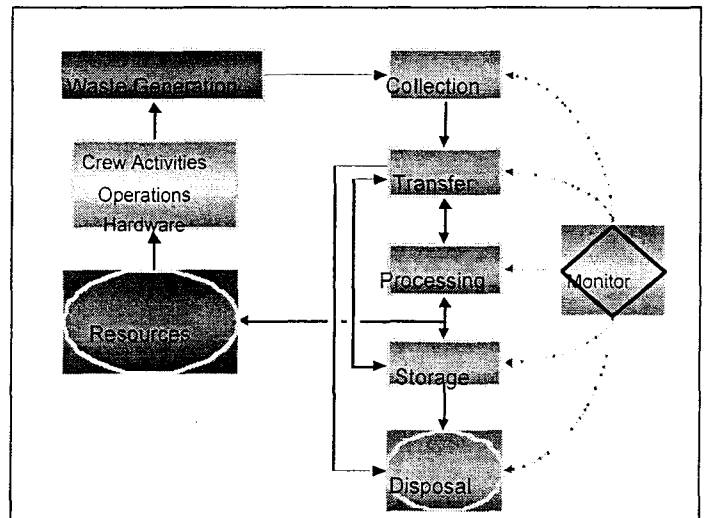
The purpose of this paper is to document the ongoing progress of SWM requirements development for future missions. Progress in this effort has been limited by both the lack of good "parent" requirements documents and the difficulty of writing good requirements for missions that are not completely defined. Some of the difficulties in writing SWM requirements for such missions are discussed in Levri et al, 2002. Since future missions have not been defined in great detail, assumptions must be made and documented during the requirements development process. As a result, most of the requirements written to this point are top-level in nature. In the following sections, both the six functions that SWM provides and assumed mission specific resource recovery requirements will be described. The six functions are acceptance, transport, storage, processing, monitoring and control, and disposal.

## SOLID WASTE MANAGEMENT FUNCTIONS

Historically, solid waste management has included acceptance, with subsequent containment/storage, transport, and disposal, with minimal to no processing. This method for managing wastes is appropriate for missions of short duration. Short-duration or near-Earth missions can use open loop life support systems, with re-supplied consumables as a source of required materials.

However, as mission duration increases, so does the need to close material loops in the system, in an effort to reduce mission costs. As mission duration increases and mission location prohibits resupply from Earth, there are cost advantages in closing material loops. (Additionally, long duration missions in locations that prohibit resupply require life support technologies of enhanced reliability.) For future long duration missions, waste processing may be a necessary SWM function. Waste processing can be used to reduce the potential hazards associated with a waste or can be used for the recovery of resources from wastes. Mission analysis must be done to determine the point at which processing of wastes for resource recovery becomes cost effective (Gertner 1999, Maxwell et al 2001, Hogan et al, 2002).

Thus, solid waste management functionality changes with mission duration and location. All six functions and their interactions are illustrated in **Figure 2**.



**Figure 2. ALS SWM Functions (adapted from Hogan, 2001, ASGSB)**

In **Figure 2**, the direction of material flow is shown with solid, black arrows. Information flow is shown with dashed, blue arrows. As shown in the diagram, all wastes must initially be accepted and transported. In this diagram, waste transport is only explicitly shown after the collection phase to either the processing, storage or disposal functions. However, waste transport inherently also takes place between the processing, storage, and disposal functions. If processing is performed, waste materials can pass repeatedly between storage and

processing, or directly from processing to disposal. If wastes are stored at any point in a mission, they can either pass to and from processing steps or directly to disposal. All functions require that waste material and processing states be monitored and controlled. Each function is discussed in detail below.

## ACCEPTANCE

As seen in **Figure 2**, the SWM element begins with the acceptance function. The acceptance function defines the types of wastes that are "acceptable" to the SWM element. In previous human space missions, materials requirements were not developed with the final end user, the waste management system, heavily in mind. More emphasis in this area will be needed in future missions. By defining types of acceptable wastes, SWM can identify nuisance wastes and consumables prior to a mission. Doing this well in advance of mission design should forecast problems and allow for alternate material types or waste system designs to be investigated.

In order to plan for future missions, a waste generation schedule and collection location must be predicted. Thus, waste acceptance interfaces must be defined prior to design of a SWM subsystem. For instance, the toilet will likely be the acceptance interface at which some materials from the crew become a part of the SWM subsystem. However, the design of the toilet might not be the responsibility of the SWM Element; toilet design may be the responsibility of a Crew Systems element. Thus, the SWM Element may need to levy requirements on the interface to the toilet, thereby defining the types of wastes that can be placed in the toilet and how frequently these wastes can be accepted by the SWM subsystem. Requirements that are levied on other subsystems by the SWM subsystem can be used to assure that waste composition and generation schedule are compatible with the SWM subsystem capabilities. The solid waste generation rate for future long-duration missions will be documented in the SWM Waste Model (Drysdale et al 2002).

While, ideally, an acceptance function will be designed with adequate robustness to accept additional wastes, there are potential hazards in feeding a system with wastes that it is not certified to accept. Unauthorized wastes might damage the system, or might create a hazard for the crew. Damage might occur, for example, if metal objects are fed into a shredder. Toxic chemicals might damage bioreactors or might be released into the air.

## TRANSPORT

Transport pertains to the movement of wastes from one location to another within the SWM subsystem. Wastes must be adequately contained during transport to prevent release of hazardous or noxious materials. Transport can take place either between or within SWM

technologies. For example, transport could pertain to the movement of inedible biomass from the point of acceptance to a waste storage location. The containment unit used during that transport may simply be a bucket that was also used as the initial waste acceptance unit, when the inedible biomass was separated from the edible portion. As another example, transport can take place within a waste processing system, such as in a case where biomass slurry is pumped between a size reduction unit and an oxidative processor. In that case, the containment unit during transport would be the pump and tubing that connects the size reduction unit to the oxidative processor.

## PROCESSING

The processing function performs any necessary change in the quality of a waste. The processing function may be needed for one or more of the following four purposes: 1) to recover resources, 2) to meet solid waste storage requirements, 3) to meet solid waste transport requirements, and 4) to meet solid waste disposal requirements. The processing need that has historically received most attention in the ALS Project has been resource recovery from solid wastes.

The need for waste processing cascades from top-level requirements. For example, top-level requirements in the area of microbial safety can drive the need for processing feces into material that is less microbially active. As another example, a system-level water mass balance may reveal the need for water recovery from waste materials, if that approach is cost-effective.

## STORAGE

Storage is short- or long-term temporary containment of wastes, with planned access. If there is a time lag between any two SWM functions, wastes must be appropriately stored during that time. The appropriate type of storage is highly dependent upon both the type of waste material, the amount of time that it must be stored, and subsequent need for access. Some wastes may require processing in order to stabilize materials prior to storage. Analyses must be performed to determine the best combination of pre-storage processing and level of containment. For example, other things being equal, feces that are processed to reduce microbial activity prior to storage may require a lesser degree of containment than stored feces that has not been processed.

## DISPOSAL

The disposal function provides the means to discard any waste (either processed or unprocessed) that has been identified as requiring no further planned access or transport. Such waste may be contained and stored either within, or external to, the habitable volume of the space environment. Disposed waste may also be

transferred to a spacecraft for return to Earth (e.g. ISS to Shuttle). Any waste material that is not a recoverable resource must ultimately be either stored or disposed. The disposal method is highly dependent on mission location. Other requirements (e.g. planetary protection) will have significant effects on our ability to dispose of waste outside of the habitat. Once a solid waste has been disposed of, it is no longer "the responsibility of" the solid waste management system.

## MONITORING AND CONTROL

Monitoring and control is needed to assure safe and efficient operation of solid waste management technologies. The state of wastes and processes must be monitored and then appropriately controlled to maintain safe and effective conditions. The necessary level of monitoring and control is both waste- and process-specific. The SWM subsystem monitoring and control system will probably need to integrate with a higher-level control system (e.g. SCADA – supervisory control and data acquisition) that is responsible for controlling system level responses. Ideally, a standard computer communication protocol would be used for this purpose (Young et al 2002).

## RESOURCE RECOVERY

Resource recovery is one of the possible motivations for processing wastes. For all missions, resource recovery requirements need to be initiated at the system or mission level. Analysts must evaluate different subsystem configurations to estimate the best method for obtaining and/or conserving a particular resource (e.g. water). Analyses could suggest that recovery of such resources from waste materials may be cost-effective. In such a case, R&TD would be carried out to develop technologies for recovering such resources. The ALS Program has had extensive focus on developing resource recovery technology for future space missions, particularly in solid waste processing. Such efforts stem from research on Closed Ecological Life Support Systems (CELSS), begun in the 1960s (Slavin et al 1986, Wallace et al 1990), and from earlier terrestrial work done with domestic, industrial, agricultural, and shipboard wastes.

The degree of material loop closure can range from no closure (complete resupply from Earth) to complete closure (all waste materials would ultimately be recycled). Analysis must be used to outline the costs and benefits associated with closing material loops within a life support system. With respect to mission duration, significant closure of both air and water loops will typically pay off prior to beginning solid waste loop closure. The break-even points for the different options for waste loop closure are difficult to determine. For the ALS missions being considered in this paper, no system level requirements had been developed prior to the recent efforts of the SWM Element. The requirements

identified in this paper should be considered to be preliminary.

The resource recovery requirements that are posed in this paper will be used to aid in identification of technologies for ALS SWM R&TD, as illustrated in block 11 of **Figure 1**. For more detailed information about any of the missions discussed in this paper, the reader is referred to the ALS RMD. It is important to note that this is a preliminary set of suggested requirements that should be re-evaluated periodically. Significant advancements in technology may warrant changing the requirements. For example, considerable improvement in crop lighting efficiency can have large impacts on the expected top-level life support architectures of the missions in the RMD. If top-level life support architectures change, so may the lower-level requirements.

## ISS MISSION - POST PHASE III WITH ALS TECHNOLOGIES

In the ALS RMD, there are several ISS configurations. For the purposes of developing requirements for ALS systems, "Post Phase III with ALS Technologies" is the configuration of interest, because it is the version with the greatest application of ALS technologies.

For ISS missions, it is assumed that water is the only resource of interest in waste materials. Water is a major constituent of both wet trash and fecal wastes. By focusing on water recovery, a potential exists to further close the water system on ISS.

## MARS DUAL LANDER MISSION

The Mars Dual Lander Mission architecture supports a crew of six persons and employs three vehicles: a Mars Transit Vehicle, a Surface Habitat Lander, and a Mars Descent/Ascent Lander (Drake, 1999). The transit voyage to Mars in the Mars Transit Vehicle is expected to nominally take 180 days. Once the crew arrives in Mars orbit, they transfer to the Mars Descent/Ascent Lander and descend to the Martian surface. The surface mission nominally lasts 600 days, during which the crew resides in the Surface Habitat Lander. During the surface portion of the mission, the Mars Transit Vehicle awaits in untended stand-by mode in Mars orbit, while the Mars Descent/Ascent Lander waits in stand-by mode on the Martian surface. After the surface mission, the crew ascends to Mars orbit in the Ascent/Descent Lander and transfers to the Mars Transit Vehicle for return to Earth. The return voyage nominally requires 180 days. The expected top-level life support system architecture for each segment will now be discussed.

## Transit Vehicle

In the Transit Vehicle, it is expected that the crew would consume mostly prepackaged food. However, it is plausible that a small salad machine might be available to provide fresh greens as a supplement to the crew's diet. Extravehicular activity (EVA) operations are not expected to be performed during transit. Water is assumed to be the only resource requiring recovery from solid wastes. Whether this is appropriate from a system perspective is highly dependent on the other sub-systems of the transit vehicle life support system. One driving issue is whether or not the transit vehicle will be water limited, since water will not be lost via EVA (RMD). There may be enough water contained in the food supplies to make recovery of water from wastes of limited benefit. There is a trade off between degree of hydration of the food and the amount of water recovered from wastes and other sources. (Adequate palatability and nutrition would, of course, have to be assured for any option selected.)

## Ascent / Descent Vehicle

The ascent/descent vehicle (ADV) is needed to take the crew to and from Mars orbit and the Martian surface. As the vehicle is expected to be used by the crew for only a short period of time (30 days or less), there will be no requirements for resource recovery from wastes. However, if the duration of this mission segment is extended or alternate uses for this vehicle are proposed, this vehicle's life support capabilities will be revisited. The question of water balance for the ADV has not been definitively settled.

## Mars Habitat

Throughout the surface mission, the crew will be performing EVA to support predefined scientific objectives. EVA life support is assumed to be largely open loop. Thus, extensive EVA operations will result in a loss of materials from the system. It is questionable if plant production will be cost-effective for a mission of this duration. To take a conservative position, the crew is expected to consume mostly prepackaged foods, with the possibility of producing fresh salad crops in a small biomass chamber, for increased crew satisfaction. Therefore recovery of CO<sub>2</sub> from waste materials is not anticipated to be useful. However, it is anticipated that water recovery from waste materials will be useful. In fact, maximizing water recovery might be important, and food might be more hydrated than otherwise. The RMD assumes that ISRU is not used.

## MARS BASE MISSION

The Mars base is a separate mission that would involve establishing a semi-permanent facility on Mars, supported by transit missions to change out the crew

and supply the base. Nominally, a transfer opportunity between Earth and Mars occurs once every 26 terrestrial months. Thus, assuming the first permanent crew members stay at least 600 days on Mars and the last crewmembers leave when the seventh transfer opportunity to Earth opens, the facility lifetime is 600 days plus 13 years, or 14.6 years. A mission of this duration warrants the development of significant biomass production to augment the food supply, air revitalization and water recovery. The types of wastes generated for this mission will be different from those generated on the Mars Dual Lander mission. Namely, significantly more inedible plant biomass and less food packaging wastes will be produced.

The potential resources to be recovered on this mission include water, carbon dioxide (to supplement crop growth), and inorganic plant nutrients. Additional carbon dioxide may be needed above the human metabolic production to meet carbon dioxide requirements of the Biomass Production system. If required based on system analysis, wastes will be oxidized to recover carbon. Also, potential exists for inorganic nutrient recovery from inedible plant material to become cost effective.

## OTHER MISSIONS

For the previously described ALS missions, it has been proposed in the RMD that stabilized trash could be used as radiation protection. Any mass used between the external radiation environment and the internal habitat could be used as radiation shielding but the relevant effectiveness still needs to be determined. Waste would be predominantly composed of light elements, which produce less secondary radiation when used for shielding. However, some estimates of the mass required for radiation shielding (Trinpathi et al, 2001, ICES 2001-2326) would exceed the available waste by greater than an order of magnitude, apart from operational issues.

## CONCLUSION

This paper is the last of a series of papers outlining the difficulties in developing SWM requirements for future space missions, and focuses on the results of requirement development up until now.

Six general solid waste management functionalities have been identified for future human space missions. These functionalities are further defined and include acceptance, transport, storage, processing, monitoring and control, and disposal.

Requirements for resource recovery were defined for previously described ALS missions. Results of these preliminary assessments are as follows:

- SWM shall assume to recover water from solid wastes for the following missions - ISS Phase III with ALS Technologies, Mars Dual Lander Mission (both Transit Vehicle and Mars Habitat mission legs), and Mars Base Mission.
- SWM shall also assume recovery of both CO<sub>2</sub> and inorganic nutrients from solid waste on the Mars Base Mission.

All SWM requirements will need to be supported by system level analysis, which up to now have not been completed.

## ACKNOWLEDGMENTS

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## DEFINITIONS, ACRONYMS, ABBREVIATIONS

ADV: Ascent / Descent Vehicle  
 AHP: Asset Hierarchy Procedure  
 ALS: Advanced Life Support  
 CELSS: Closed Ecological Life Support Systems  
 EVA: Extra-vehicular Activity  
 ISS: International Space Station



LSS: Life Support System

R&TD: Research and Technology Development

RMD: Reference Missions Document

SCADA: Supervisory Control and Data Acquisition

SIMA: Systems Integration, Modeling and Analysis

SWM: Solid Waste Management

TRL: Technology Readiness Level